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CONTACT PRINTED MASKS FOR 3D MICROFABRICATION IN NEGATIVE RESISTS

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ABSTRACT

We present a process based on contact printed shadow masks for three-dimensional microfabrication of soft and sensitive overhanging membranes in SU-8. A metal mask is transferred onto unexposed SU-8 from an elastomer stamp made of polydimethylsiloxane. This mask is subsequently embedded into the negative resist to protect buried material from UV-exposure. Unlike direct evaporation-deposition of a mask onto the SU-8, printing avoids high stress and radiation, thus preventing resist wrinkling and pre-polymerization. We demonstrate effective monolithic fabrication of soft, 4-µm-thick and 100-µm-long cantilevers integrated in a microfluidic system. The process yields very flat and well-defined membrane surfaces.

1. INTRODUCTION

Microfabricated structures are increasingly coupled to biology and medicine to produce analytical systems for biochemical and medical diagnostics. Such lab-on-a-chip devices are usually composed of a microfluidic handling system, which can incorporate complex mechanical structures such as valves and pumps. Vital to the fabrication of these components is the ability to three-dimensional structuring. In recent years SU-8, an epoxy-based negative UV-sensitive photoresist [1], has received increasing attention in microfabrication due to its out-standing properties in thick-film processing at high aspect ratio. Unlike the traditionally used silicon and glass, SU-8 is a low-cost material and exhibits high biocompatibility. The polymer is micromachined by cheap and simple spin-coating and UV lithography techniques allowing for short fabrication times and high flexibility in device prototyping. Fully three-dimensional microfabrication in SU-8 is achieved by staking of individual polymer layers.

We present here a novel process for three-dimensional, monolithic fabrication of very thin and soft membranes in SU-8. This work was motivated by our research in cantilevered biosensors. Such biosensors provide information on biochemical reactions on the molecular scale. They monitor changes in surface stress provoked by e.g. antibody-antigen binding or DNA hybridization occurring on the cantilever. Crucial to these devices is a very soft cantilever for high stress sensitivity. Initially fabricated in silicon and silicon nitride [2] we recently manufactured such biosensors in SU-8 with full integration in a microfluidic network [3]. SU-8 has a 40 times lower Young's modulus than silicon, which can potentially increase the sensor sensitivity due to the softer material. Negative resists such as SU-8, however, impose an inherent difficulty in fabrication as illustrated in Fig. 1. Fig. 1(a) shows a cross-sectional view of a cantilever overhanging a microfluidic channel. The manufacturing of the cantilever requires the exposure of only a thin layer on the film surface while leaving the bulk material unaffected by radiation. Due to the low absorption of SU-8 in the near-UV region this task becomes rather challenging when employing standard UV lithography. The problem can be circumvented by composing structures as shown in Fig. 1(a) via time-consuming and cumbersome bonding of two chips [3]. Here, we suggest the use of contact printed embedded masks to protect buried resist from UV-exposure [Fig. 1(b)] offering a simpler and faster way to fabricate particularly thin (< 5-µm-thick) and sensitive overhanging structures. Such embedded shadow masks have been used earlier; however, they were directly evaporated onto the soft, unexposed SU-8 [1]. By using this technique we observed warping of the resist after metal deposition in an electron beam evaporation device (LAB 500, Leybold Optics, Alzenau, Germany). The polymer deformation is supposed to origin from interfacial stress between the metal and polymer provoked by thermal mismatch of the two materials. Moreover, polymerization of the SU-8 due to UV-light and scattered electrons generated during the evaporation process was observed. While warping and pre-polymerization of the SU-8 is negligible when working with thick (> 50 µm) resists [1] it proved to be fatal for very thin membranes [3]. Other techniques such as proton beam exposure [4], UV dosage control [5] and laser writing [6,7] are either expensive or produce stiff membranes of several tens of micrometers thickness. The use of sacrificial layers [8] produces edges in thin SU-8 films, which can cause cracks in the polymer and lead to bad step coverage in metal wires on top of the structure. In the following, a protocol for contact printing of

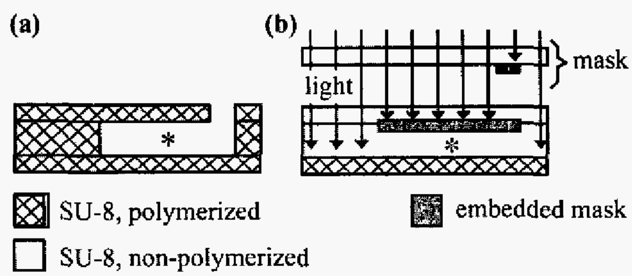

Figure 1: (a) Difficulty in monolithic fabrication of overhanging structures in negative resist: selective polymerization of resist over non-polymerized (*) material. (b) Principle of embedded mask to protect buried resist (*) from UV-induced polymerization.

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embedded masks is provided. The process minimizes plastic deformation of the resist material by avoiding direct evaporation-deposition of the metal mask onto the resist. The fabrication of well-defined, soft and sensitive cantilevers integrated in a microfluidic handling system as illustrated in Fig. 1(a) is demonstrated.

2. FABRICATION PROCESS

Stamp

The process sequence for the fabrication of the overhanging cantilevers is schematically illustrated in Fig. 2. The central step in the protocol consists of contact transfer printing [9] of the embedded mask from a soft stamp made of polydimethylsiloxane (PDMS) onto the SU-8 resist [Fig. 2(a)]. The high mechanical flexibility of the elastomer stamp ensures conformal, intimate physical contact between the tool and the substrate on wafer scale. The stamp was molded against a negative master consisting of a 17-µm-thick structured SU-8 film on a silicon wafer. The liquid prepolymer (Sylgard 184, Dow Corning Corp., Midland, MI, USA) was first poured onto the master and then cured in an oven at 80 °C for 4 h. After curing the PDMS the stamp was peeled off the mold. It should be noted that the elastomer shrinks about 1 % after its release. This shrinkage needs to be taken into account when fabricating the master to ensure proper alignment between the mask to be stamped and components on the SU-8 microsystem.

Finally, a 50-nm-thick layer of gold followed by a 20-nm-thick chromium film was evaporation-deposited on the stamp without any surface pretreatment. This metal bilayer formed the shadow mask to be transferred onto the SU-8. We calculated the penetration depth of light into gold in the near-UV range to about 16 nm (for intensity). A 50-nm-thick film therefore provides enough light attenuation for reliable masking. We note that gold and PDMS exhibit a low surface free energy leading to very poor adhesion between the two materials. The poor adhesion is crucial for the transfer printing process since it facilitates the release of the metal film from the stamp. The chromium film, on the other hand, is known to be more reactive promoting the adhesion of the mask to the SU-8 resist [3].

Substrate

The cantilever microsystem was fabricated on a silicon wafer easing the handling of the polymeric substrate. The wafer was first coated with a 50-nm-thick fluorocarbon layer produced by plasma-polymerization of C_4F_8 in a silicon dry etch device (ASE, STS-Surface Technology Systems plc, Newport, UK). This film reduces the adhesion of the polymer to the silicon due to a low surface free energy and facilitates the final release of the chips after the micromachining was completed. Next, a 30-µm-thick bottom layer of fully processed SU-8 (soft-baked, UV-exposed, post-exposure-baked) and a 50-µm-thick layer of non-polymerized SU-8 (SU-8 50, MicroChem Corp., Newton, MA, USA) were deposited on top of the fluorocarbon film [Fig. 2(a)]. The non-polymerized SU-8 layer was only soft-baked to evaporate the solvent. It was designated to host the microfluidic channel defined later after printing of the embedded mask.

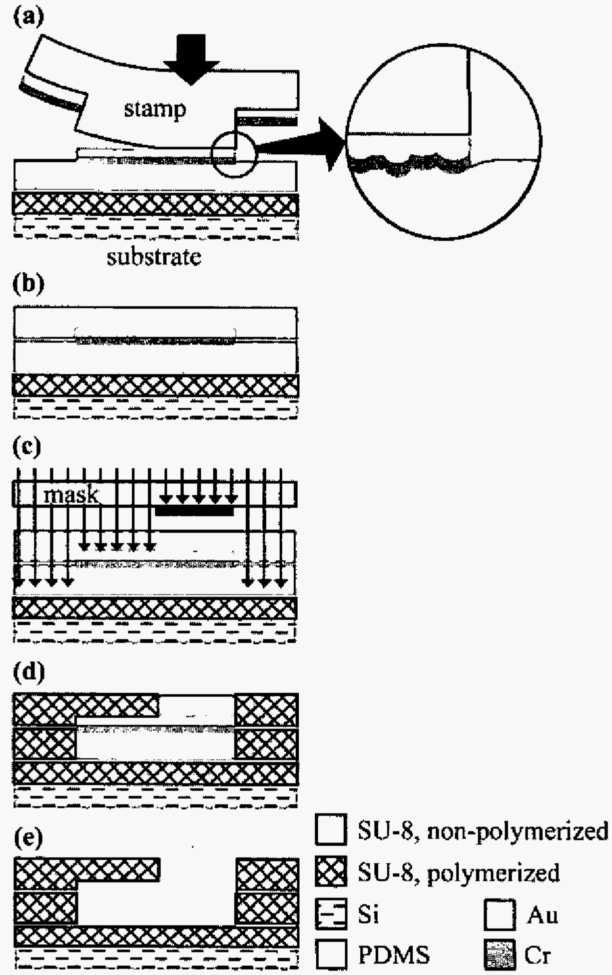

Figure 2: Process sequence for the fabrication of overhanging cantilevers in SU-8. (a) Contact printing of the mask on a SU-8 substrate composed of a polymerized bottom layer covered by a non-polymerized layer. The image shows a schematic cross-section of the stamp and substrate. (b) Spin-on of a thin SU-8 layer on top of the stamped mask. (c) Standard UV-light lithography to define the cantilever and the microchannel. The embedded mask protects the underlying resist from light exposure. (d) Polymerization of the UV-exposed resist by a post-exposure bake. (e) SU-8 development and mask etching to free the cantilever.

Contact Printing

In the following, the overhanging cantilevers were fabricated on top of the non-polymerized SU-8 substrate. Therefore, the non-polymerized resist below the location where the beams were to be produced needed to be protected from UV-exposure by the gold/chromium mask. The mask was printed from the stamp onto the SU-8 at gentle pressure of

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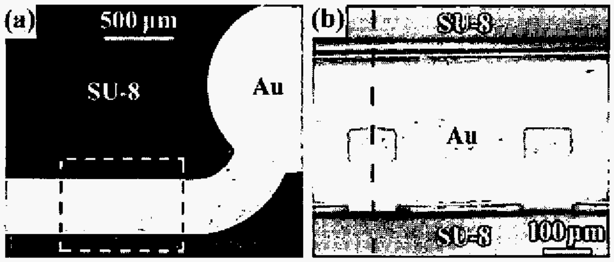

Figure 3: Optical light microscope images of the embedded mask at different process steps. (a) Mask on non-polymerized SU-8 after transfer printing from the PDMS stamp. (b) Embedded mask with cantilever structure on top after UV-exposure and post-exposure bake. The image location corresponds to the marked area in (a). The cross-section of the substrate along the line drawn in (b) is shown schematically in Fig. 2(d).

about 1 MPa for a period of 1 min [Fig. 2(a)]. During printing the SU-8 substrate was heated to 47 °C, which is close to the glass transition temperature of the non-polymerized resist. Upon peeling the stamp off the SU-8 the metal mask delaminated from the PDMS due to low adhesion and stuck to the SU-8 surface. Heating of the polymer proved to be an important parameter in the stamping process. Close to the glass transition temperature the viscosity of the non-polymerized SU-8 decreases. The soft polymer adapted to the surface roughness of the metal mask, thus filling up the gaps in the corrugated surface [magnified inset in Fig. 2(a)]. This small polymer deformation on the nanometer-scale increased the contact area and improved the adhesion between the metal and the SU-8.

The printing process left a very flat metal mask on the SU-8 as shown in the light microscope image of Fig. 3(a) and the stylus profilometer image in Fig. 4. Apart from the elevation created by the metal mask printed onto the resist, Fig. 4 also reveals grooves in the SU-8 on both sides of the mask. These troughs correspond to plastic deformation of the non-polymerized SU-8 induced by the pressure applied during the stamping. The deformation of the resist is, however, in the range of only a few hundreds of nanometers. This low surface distortion was crucial to avoid reflow and thus wrinkling of the polymer and mask during subsequent baking and polymerization steps.

After mask printing the metal-patterned resist was covered with a thin SU-8 layer of several micrometer thickness [SU-8 2, MicroChem Corp., Newton, MA, USA, Fig. 2(b)]. This film served as the substrate in which the overhanging cantilevers were defined. The substrate was left for at least 2 h at a well-ventilated place to gently evaporate the solvent. This "soft bake" at room temperature minimized reflow of the non-polymerized material below the mask. Solvent from the freshly added SU-8 film can diffuse into the underlying non-polymerized layer reducing the material's viscosity and increasing its susceptibility to plastic deformation. The SU-8 was subsequently exposed to UV-light through a standard mask as shown in Fig. 2(c). During this

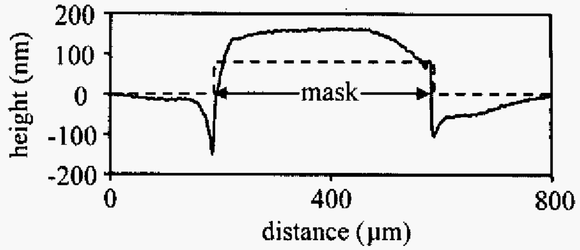

Figure 4: Surface profile across the mask printed onto non-polymerized SU-8. The solid line shows the measured topography. The dashed line reflects the theoretical profile in absence of any surface deformation induced by printing.

lithography step the cantilever and microfluidic channel layout was projected onto the resist while the embedded shadow mask protected the resist underneath the cantilevers from UV-exposure. The exposed resist was polymerized by a post-exposure bake at 40 °C for several hours [Fig. 2(d)]. The temperature during the baking was again set below the glass transition temperature of non-polymerized SU-8 to minimize material reflow. The light microscope image of Fig. 3(b) depicts the polymerized cantilever structure on top of the embedded mask after the post-exposure bake.

Development

The SU-8 substrate was subsequently developed to free the overhanging cantilevers [Fig. 2(e)]. To this end, the non-polymerized SU-8 was dissolved in propylene-glycol-methyl-ether-acetate (PGMEA) and the gold/chromium mask etched away (GE 8148 and 1020 AC, Transene Company, Inc., Danvers, MA, USA). Note that the printed mask can also be used as a perfect screen for further lithography steps to, e.g., create piezoresistive wiring on top of the cantilevers [3].

3. RESULTS AND DISCUSSION

Figs. 5(a) and 5(b) show the cantilevers depicted in Fig. 3(b) after development. They are 100 µm wide, overhanging a 50-µm-deep microfluidic channel for a length of 200 µm. The thickness of the cantilevers measures about 8 µm. In Figs. 5(c) and 5(d) cantilevers of 100 µm width and 100 µm length with a thickness of only 4 µm are shown. Unlike the experiments performed by direct evaporation-deposition of embedded masks onto SU-8 [3] the beams fabricated via mask printing are perfectly flat. This result provides evidence of the importance of a 'soft' mask fabrication technique to achieve undeformed soft and sensitive overhanging membranes. To our knowledge these cantilevers are the thinnest overhanging SU-8 membranes published to date. The beam thickness compares well with the cantilever thickness achieved by the traditional chip bonding technique [3]. In principle, by diluting the purchased SU-8 resist, the fabrication of membranes down to 2 µm thickness or less should be possible. Adding further solvent to the SU-8 be-

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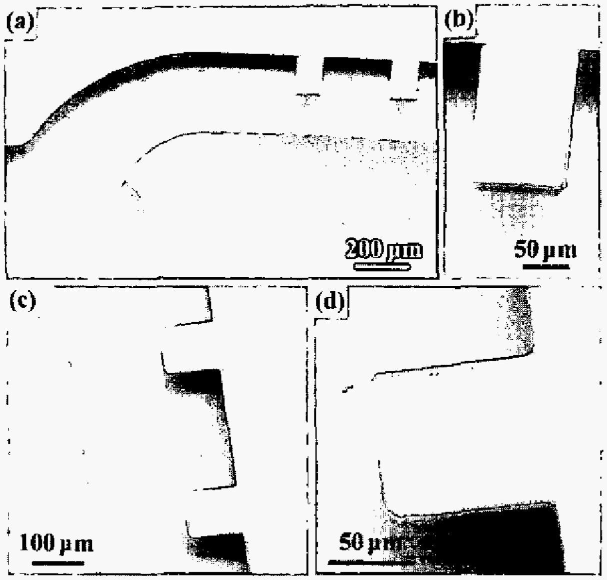

Figure 5: Electron microscope images of fully three-dimensionally microfabricated cantilevers integrated in a microfluidic channel. The thickness of the beams in (a) and (b) measures 8 µm, in (c) and (d) 4 µm. Note the flatness of the suspended structure.

fore processing allows for spin-coating of films significantly thinner than 4 µm onto the resist.

4. CONCLUSIONS

A process based on contact printed masks for three-dimensional microfabrication of highly sensitive cantilevers in SU-8 was demonstrated. The masks were transferred onto unexposed SU-8 from a flexible PDMS stamp. The mask transfer was mediated by a differential adhesion technique. Using a gold/chromium mask the gold surface facilitated delamination from the stamp while the chromium surface promoted the adhesion to the resist. Unlike evaporation-deposition, printing avoided high stress, vacuum, UV-light and electron bombardment, thus preventing resist wrinkling and pre-polymerization. The fabricated cantilevers have a very flat and well-defined surface emphasizing the importance of a 'soft' mask fabrication process to produce sensitive membranes. The microfluidic system fabricated here can be closed by applying a thick SU-8 layer over the substrate and printing a metal mask on top of it. This mask protects the resist underneath from UV-exposure during the definition of a channel lid in a further SU-8 layer spun over the metallization. Stacking of printed masks thus paves the way for complete three-dimensional micromachining on wafer scale of complex structures such as integrated cantilevered probes, valves, pressure sensors and fine filters required for lab-on-a-chip devices.

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